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SIMULATOR FIDELITY: A CONCEPT PAPER

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SIMULATION SYSTEMS TECHNICAL AREA

U. S. Army
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This report reviews the literature on simulator fidelity and shows that there is a great deal of confusion in the usage of the term fidelity. A two-aspect definition of fidelity is proposed which focuses on the physical and functional similarity of the training device to the actual equipment for which training is undertaken. This definition is discussed as it applies to several parameters of the training situation, such as type of task, trainee's stage of learning, or total training context, to determine training

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effectiveness. Methodological issues in the empirical determination of fidelity requirements are discussed. A pilot research strategy to begin the empirical study of fidelity requirements is outlined.

Technical Report 490

SIMULATOR FIDELITY: A CONCEPT PAPER

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Simulation Systems

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FOREWORD

The Simulation Systems Technical Area of the Army Research Institute for the Behavioral and Social Sciences (ARI) performs research and development in areas that include training simulation with applicability to military training. Of special interest is research in the area of simulation fidelity requirements. It is necessary to determine the necessary levels of simulator fidelity before any training system may be developed and procured for use in the Army training community.

This report surveys the relevant literature on simulator fidelity and recommends a workable definition of simulator fidelity as well as outlining an approach to the empirical determination of simulator fidelity requirements.

This report is responsive to the requirement of the Office of the Project Manager for Training Devices (PM TRADE) and to the Army's Project 2Q162717A790, "Defining Simulation Fidelity Requirements."

Joseph Zeidner

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SIMULATOR FIDELITY: A CONCEPT PAPER

BRIEF

Requirement:

To review the relevant literature on simulator fidelity in order to determine how the term fidelity has been used. From this review, to recommend a workable definition of fidelity and outline a course of empirical investigation to determine the necessary levels of simulator fidelity to insure adequate training effectiveness.

Procedure:

An extensive review of literature on simulator fidelity was conducted. It was shown that there is much confusion in the usage of the term "fidelity." A two-aspect definition of fidelity was proposed which focuses on the physical and functional similarity of the training device to the actual equipment for which training is undertaken. This definition is discussed as it applies to several parameters of the training situation, such as type of task, trainee's stage of learning, or total training context, to determine training effectiveness. Methodological issues in the empirical determination of fidelity requirements are discussed and a pilot research strategy is outlined.

Findings:

Confusion surrounding the use of the term "fidelity" may be substantially reduced if we limit the use of the term and let fidelity refer only to the degree of similarity, both physical and functional, between a training device and the actual equipment for which the training was undertaken.

Utilization of Findings:

This report can be used by researchers in determining how they may design empirical studies to determine necessary levels of simulator fidelity and by the military training community to determine the nature of training devices, which must be designed and procured.

SIMULATOR FIDELITY: A CONCEPT PAPER

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SIMULATOR FIDELITY: A CONCEPT PAPER

Today's Army is faced with training problems like none previously encountered in that the high technology of its advanced weapons systems requires correspondingly sophisticated operators and maintainers. This requirement places a heavy burden on training, particularly given the prevalence of large numbers of Category IV enlistees. The traditional approach of training personnel on actual equipment is becoming more and more prohibitive because of the cost of these systems. To cope with this prohibitive expense and to improve the effectiveness of its training, the Army has and will continue to turn increasingly toward the use of simulators. This movement is being paralleled by the other armed services (Miller, 1974; Spangenberg, 1976; Fink & Shriver, 1978; Purifoy & Benson, 1979; Malec, 1980). Apart from potential cost savings, simulators have several unique instructional advantages over the use of either the classroom or actual equipment for training.

Spangenberg (1976) discusses seven unique advantages of simulation for training. Simulators can (1) provide immediate feedback, (2) increase the number of crises, conflicts, equipment malfunctions, and emergencies to provide the trainee with experience which would be unavailable on actual equipment, (3) compress time so a complex sequence of tasks may be accomplished in the time it would take to run through only one or two tasks on the actual equipment, (4) vary the sequence of tasks to maximize training efficiency, (5) provide guidance and stimulus support to the trainee in the form of prompts and feedback, (6) vary the difficulty level to match the skill level of each individual trainee, and (7) provide the trainee with an overview from which the trainee may form an overall understanding of the whole situation. These advantages, in addition to their potential cost-effectiveness have led the Army (PM TRADE) to the conclusion that simulators should be utilized to greater advantage in its training program.

But though they are intended to reduce training costs, training simulators may not be cost effective if they duplicate the physical and functional characteristics of operational equipment more precisely than is required for effective transfer of training, i.e., if simulation fidelity exceeds training requirements. However, designing the appropriate level of fidelity is not an easy task. At the very least, a set of consistently used operational definitions of fidelity is required. The term fidelity has been used with a variety of meanings and it is vital that we agree on a workable definition if we are to develop user-oriented guidance in the design, acquisition, and deployment of training simulators. This paper attempts to develop such a definition of fidelity by reviewing and synthesizing the relevant literature. The paper then attempts to place the concept in the proper context of the Army's training needs. Finally, it outlines a variety of strategies for implementing further research to determine specific fidelity requirements for the wide range of tasks carried out by the modern Army.

DEFINITIONS OF FIDELITY

The literature on simulation for training discusses the problem of the necessary levels of fidelity in simulators. The concept of fidelity is unclear because it has been used in a wide variety of ways with a wide variety of meanings. This section surveys the relevant literature and delineates the most widely used definitions of fidelity. Some definitions are very general while others tend to be more specific.

General Approaches to the Definition of Fidelity

Several recent discussions of training simulation have taken a general approach to the definition of fidelity. Two instances will serve as exemplars of this approach. Miller (1974) states that fidelity refers to the accuracy of reproduction of the actual equipment by the simulator; it is the degree to which a simulator resembles the real operational equipment or situation. An even more general approach is taken by Malec (1980). He states that fidelity has been achieved if activity on the simulator is "sufficiently like exercising the actual equipment" (Malec, 1980, p. 16). Neither of these definitions is sufficiently precise or operational to be useful in the development of guidance for simulator designers. We must know what "similar" means or what to be "sufficiently like" the actual equipment entails. There have been other definitions of fidelity which are much more specific than those above.

Specific Breakdowns of Fidelity

One of the most frequently cited breakdowns of the concept of fidelity was provided by Kinkade and Wheaton (1972). They detail three types of fidelity: equipment, environmental, and psychological.

- Equipment fidelity is the degree to which the simulator duplicates the appearance and "feel" of the operational equipment.
- Environmental fidelity is the degree to which the simulator duplicates the sensory stimulation (excluding control feel) which is received from the task situation.
- Psychological fidelity is the degree to which the simulator is perceived by the trainee as being a duplicate of the operational equipment and the task situation.

(Kinkade & Wheaton, 1972, p. 679)

Kinkade and Wheaton provide examples of each of these types of fidelity. Equipment fidelity would be high for a driver trainer designed to teach driving if "an actual automobile cab, with steering wheel, steering wheel feedback dynamics, speedometer, fuel gauge, etc." (Kinkade & Wheaton, 1972, p. 679) were included. Environmental fidelity would be high if the trainer provided "motion cues and a three-dimensional, dynamic visual presentation of the external world (i.e., the road, trees, sky, etc.)"

(Kinkade & Wheaton, 1972, p. 679). Finally, the level of psychological fidelity would be high if the trainee perceives the simulator as being highly realistic, even though it might deviate substantially from the actual equipment it is supposed to represent. These three types of fidelity do not cover all aspects of the concept.

A series of four papers (Wheaton, Mirabella, & Farina, 1971; Wheaton & Mirabella, 1972; Mirabella & Wheaton, 1974; Prophet & Boyd, 1970) discuss task fidelity. Task fidelity refers to the correspondence between tasks performed on the actual equipment and tasks performed on the training simulator. A similar behavioral approach to fidelity is taken by Matheny (1978). We thus have four facets to the concept of fidelity so far. One facet deals with the physical configuration of the simulator (equipment fidelity), one deals with the total context which the simulator tries to duplicate (environmental fidelity), one takes a perceptual viewpoint (psychological fidelity), and finally we have a behavioral approach (task or behavioral fidelity). Some approaches do not break the concept of fidelity down quite so much.

Fink and Shriver (1978) discuss only two types of fidelity--functional and physical fidelity. Functional fidelity is the attempt to represent faithfully the stimulus and response options provided by all or portions of a piece of equipment. The previous example of the motion and visual cues in a driver trainer would also be an example of functional fidelity. Physical fidelity is the attempt to represent accurately the appearance and "feel" of the actual equipment. The example of the parts included in the driver trainer is also an example of physical fidelity. Fink and Shriver's designations of functional and physical fidelity correspond to Kinkade and Wheaton's designations of environmental and equipment fidelity respectively. The term "psychological fidelity" is not used by Fink and Shriver. This may be because they consider it a function of the other two types of fidelity.

Slenker and Cream (1977) not only leave out psychological fidelity but physical fidelity as well. They discuss only functional fidelity. This they define as the attempt to duplicate all of the stimulus conditions of the actual equipment. They apparently consider functional fidelity to encompass physical fidelity. This approach would therefore be guided by precise stimulus analysis to ensure that the simulator provided the same cues as provided by the actual equipment.

Freda (1979) defines fidelity as having two aspects. Physical fidelity is the "engineering (hardware) representation of features in the operational equipment" and psychological fidelity is the "behavioral (functional) representation of the information processing demands of the operational equipment" (Freda, 1979, p. 2). This approach approximates that of Fink and Shriver (1978). Freda's physical fidelity agrees with physical fidelity, as defined by Fink and Shriver. Freda's psychological fidelity is very close to Fink and Shriver's functional fidelity. Any differences between these two approaches are those of emphasis. Freda appears to focus more closely on the trainee through the behavioral aspects of "psychological" fidelity while Fink and Shriver focus on the hardware through the stimulus and response aspects of "functional" fidelity. Since one may define

behavior as stimuli and responses, it is not difficult to see the parallel between these two approaches.

It can be easily seen that the term fidelity has been used in a variety of contexts. Hardware, environmental, perceptual, and behavioral applications of the term fidelity tend to obscure one's understanding of the term. In addition, different "types" of fidelity are used to label the same concept, such as equipment and physical fidelity or environmental and functional fidelity. The application of the term "fidelity" in so many contexts and in so many variations constitutes an overextension of the term and negates the usefulness of the concept. We need more consistency and clarity in our definitions of fidelity concepts if they are to be useful in the design of training simulators. Perhaps fidelity concepts have been developed too academically and our efforts should be directed to other areas that are oriented more toward applications.

Often it is possible to gain greater understanding of a concept if we study the way it is used by practitioners as opposed to researchers. In other words, let us now change the direction of our focus from the academic side to the more pragmatic approach taken by contractors who actually attempt to build simulators and by the armed services which attempt to provide user guidance in evaluating and procuring the devices that the contractors build.

Simulator developers have not been much more successful in consistently conceptualizing fidelity. Consider for example the work of four potential contractors who submitted designs for a proposed maintenance training simulator, the Army Maintenance Training and Evaluation Simulation System (AMTESS).

Hughes Aircraft Corporation (1980) takes a two-factor approach to the definition of fidelity. They define physical fidelity as the degree of realism presented in every sensory mode. This seems to be a combination of both of Fink and Shriver's distinctions, physical and functional fidelity. Realism of simulator controls as well as realism in the way the controls are displayed and the total environment in which the simulator is used would be indicators of physical fidelity, as the term is used by Hughes. Hughes also uses the term "psychological fidelity" in a new sense. It is defined as how fully the training environment exercises the mental skills required in performing the job tasks. Other distinctions of fidelity are also made, such as behavioral fidelity, engineering fidelity, and equipment fidelity, but it is not clear (at least to this reviewer) how these terms are used by Hughes.

Seville Research Corporation (1980) defines fidelity as the details of the characteristics of the equipment or item which are represented in the simulation and the "mode" in which those details are represented, and which are specifically included for training purposes. This approach analyzes fidelity in terms of the entire training context. The equipment characteristics may need to be modified to deal with different tasks or stages in the training process. They emphasize, however, that the question of fidelity only concerns those characteristics which need to be included to enhance training effectiveness and not those related to maintainability, reliability, or cost.

Grumman Aerospace Corporation (1980) does not specifically define fidelity. They do allude to its definition by stating that fidelity requirements analysis specifies the degree or extent of physical and functional equipment similarity required to achieve satisfaction of the training objectives. They thus focus on physical and functional similarities of the simulator to the actual equipment in defining fidelity. They emphasize the need to analyze behavioral tasks in terms of the necessary cues which the simulator must provide to enable the trainee to discriminate among the cues provided by the actual equipment.

Honeywell Corporation (1980) does not attempt to define fidelity. They simply assume that it means the similarity of the simulator to the actual equipment. They state that it is important to determine the minimum level of fidelity necessary to train required tasks.

It can be easily seen that these practitioners are more concerned with the development of equipment rather than the development of conceptual definitions. They are willing to assume that fidelity somehow deals with the physical and functional similarity between the simulator and the actual equipment and then to design their equipment to be as similar as necessary to train to criterion levels. This approach works for the construction of simulators.

It is more difficult for the individuals who are responsible for procuring these devices because they must be able to judge the output of the contractor before they invest huge sums of money to develop the proposed training simulators. It is therefore important that they determine their fidelity requirements before attempting to evaluate proposed training simulators. There are several guidance aids which attempt to assist in this process.

Although several documents have been developed to provide guidance to the individuals responsible for procuring training devices, the limited progress in conceptualizing fidelity is still seen. For example, in Training Device Requirements Guide (1979), the concept of fidelity is discussed only in terms of the physical similarity of the displays (cues) and controls (responses) between the simulator and the actual equipment (pp. 153-160). In this case, the term fidelity is not used. Functional similarity, which compares the operator's behavior in terms of information flow from each display to the operator and from the operator to each control, is also emphasized but again without the use of the term fidelity. This document makes it very clear that the most important factor is not the physical similarity of the simulator "but whether the operator acts on the same amount of information in the same way in both operational and training situations" (p. 157). A simulator might be physically dissimilar to the actual equipment (i.e., a flat panel device) and still provide the information the trainee requires to perform in the operational setting. This document provides guidelines for the analysis of tasks to be trained and also for the analysis and evaluation of the simulator in terms of physical and functional similarity.

A similar approach is taken by Interservice Procedures (1975), a TRADOC procedures pamphlet. Although this publication uses the term "fidelity" in a different context than discussed previously (here it refers to how well

the actions, conditions, cues, and standards of the Job Performance Measures approximate those of the tasks), it nevertheless acknowledges the importance of task analysis in the development of training devices. This pamphlet provides guidelines for the analysis of physical characteristics and behavioral requirements.

An approach which avoids the use of the concept of fidelity in the selection of training devices is the TRAINVICE II model (Swezey & Evans, 1980). This model incorporates techniques from both of the previous publications to analyze the physical and functional characteristics of the training devices and also the behavioral requirements which must be trained. As with both of the other guidebooks discussed, this model focuses upon the importance of both the physical and the functional characteristics of the simulator or other training device. The term "fidelity" is not employed in this discussion and it is not a comparison of simulator characteristics with operational equipment characteristics but rather a comparison of simulator characteristics with learning guidelines.

An additional guidebook for training device design was developed by Honeywell for the Air Force Human Resources Laboratory (Miller, McAleese, & Erickson, 1977). This guidebook defines fidelity as "the degree of correspondence between operational and simulation devices in terms of cues, responses, and actions that can be performed" (pp. 51-52). According to this guidebook, the level of fidelity may be determined by task analysis. Tasks are analyzed in terms of criticality, frequency, and difficulty. Task statements are developed and subsequently used to determine the necessary level of fidelity for the device designed to train the tasks.

One other publication which addresses this issue is provided by the Air Force Human Resources Laboratory (Purifoy & Benson, 1979). This model discusses four considerations which must be evaluated when discussing the appropriate levels of simulator fidelity. They are environmental conditions, stimuli, response situations, and control-display relationships. In this guidebook, fidelity is viewed in the whole training context. It is assumed that fidelity cannot be isolated but must be incorporated into an overall training requirements analysis. Here we must not only deal with physical and functional similarity but also how similarity levels interact with other variables in the training situation. A similar conclusion is reached by Eddowes & Waag (1980). They define fidelity as the physical similarity of the learning environment to the performance environment and feel that a simulator must be incorporated into the total training context if it is to be effective.

RECOMMENDED APPROACH TO FIDELITY

Table 1 shows the variety of fidelity terms that were discussed previously. It can easily be seen that many terms have been used in connection with the term "fidelity." Not only have many different terms been used, but various fidelity concepts have been described with different labels. Table 2 shows how several of the same concepts have been labeled with various terms. Variations in terminology and multiple labeling of concepts tend to confuse the issue, so it is important to realize that the

Table 1

Varieties of Fidelity Terms

Author/publication	Fidelity terms used
Kinkade & Wheaton (1972)	Equipment fidelity Environmental fidelity Psychological fidelity
Wheaton, Mirabella, & Farina (1971)	Task fidelity
Matheny (1978)	Behavioral fidelity
Fink & Shriver (1978)	Physical fidelity Functional fidelity
Slenker & Cream (1977)	Functional fidelity
Freda (1979)	Physical fidelity Psychological fidelity
Seville (1980)	Fidelity (total context)
Grumman (1980)	Physical fidelity requirements Functional fidelity requirements
Honeywell (1980)	Similarity
Training Device Requirements Guide (1979)	Physical similarity Functional similarity
Interservice Procedures (1975)	Fidelity of job performance measures
Miller, McAleese, & Erickson (1977)	Degree of correspondence (cues, responses, actions)
Purifoy & Benson (1979)	Fidelity (total context)
Eddowes & Waag (1980)	Physical similarity

Table 2

Overlapping Fidelity Concepts

Concept	Fidelity terms used	Author/publication
Physical fidelity	Physical	Fink & Shriver (1978)
	Equipment	Kinkade & Wheaton (1972)
	Functional	Slenker & Cream (1977)
	Physical	Freda (1979)
	Physical	Hughes (1980)
	Fidelity (context)	Seville (1980); Purifoy & Benson (1979)
	Physical requirements	Grumman (1980)
	Physical similarity	Honeywell (1980); Training Device Requirements Guide (1979); Eddowes & Waag (1980)
	Physical correspondence	Miller, McAleese, & Erickson (1977)
Functional fidelity	Functional	Fink & Shriver (1978)
	Environmental	Kinkade & Wheaton (1972)
	Functional	Slenker & Cream (1977)
	Psychological	Freda (1979)
	Fidelity (context)	Seville (1980); Purifoy & Benson (1979)
	Functional requirements	Grumman (1980)
	Functional similarity	Honeywell (1980); Training Device Requirements Guide (1979)
	Functional correspondence	Miller, McAleese, & Erickson (1977)
Behavioral	Task fidelity	Wheaton, Mirabella, & Farina (1971)
	Behavioral fidelity	Matheny (1978)
	Psychological fidelity	Hughes (1980)
	Job performance measure	Interservice Procedures (1975)
Perceptual	Psychological	Kinkade & Wheaton (1972)

issue is the acquisition by the trainees of skills which they may use on the actual equipment. We are thus concerned with behavior, and it is important that we not confuse fidelity with this. Fidelity has been defined in terms that cover the entire gamut from physical characteristics of the training simulator to the perception of the trainees and their behaviors. In the opinion of this author, the term "fidelity" should be restricted to descriptions of the configuration of the equipment and not be used when discussing behaviors. We must ultimately measure and evaluate behaviors, but there are many concepts already available such as sensation, perception, learning, retention, or reinforcement to deal with these. The issue of fidelity only becomes muddled if we attempt to use the same term to cover all the various aspects of the training situation. This is not to say we should throw out the remainder of the gamut. Rather, we should use labels for these concepts that do not confuse them with fidelity.

Of the approaches discussed above, the one which best isolates the equipment characteristics from the behaviors of trainees on the equipment is the approach of Fink and Shriver (1978). As was stated previously, Fink and Shriver only discuss functional and physical fidelity. In both functional and physical fidelity we are concerned with the equipment on which training is to proceed. The following definition of fidelity is therefore proposed:

> Fidelity is the degree of similarity between the simulator and the equipment which is simulated. It is a measurement of the physical characteristics of the simulator (physical fidelity) and the informational or stimulus and response options of the equipment (functional fidelity).

With this restricted use of the term fidelity in mind, let us now discuss why the level of simulator fidelity need not necessarily be as high as possible.

REASONS FOR DEPARTURE FROM HIGH FIDELITY

In his considerations for the designs of simulators, Miller (1974) states that studies have never shown that high fidelity is associated with poorer training. This statement may not be true. In a study by the Air Force (Martin & Waag, 1978), it was shown that flight simulators with very high fidelity (6 degrees of motion) provided too much information for novice trainees and actually detracted from simulator efficiency. There are also other considerations which force the designers and procurers of training simulators to desire lower levels of fidelity.

Cox et al. (1965) studied the effects of a wide variety of fidelity levels on the training of fixed-procedures tasks. They concluded that the requirements for fidelity are really quite low as long as the controls and displays of the device remain clearly visible to the individual trainee and as long as the functional relations between parts are maintained. They are careful to state that these conclusions apply only in a fixed-procedures task paradigm. It is probably safe to conclude that at least some departures from high fidelity will not produce detrimental effects in the training effectiveness of a simulator on other types of tasks. Since high fidelity is

associated with higher simulator costs, it is prudent to determine just how much fidelity is necessary in a training simulator.

Blaiwes et al. (1973) state four reasons for departure from perfect physical fidelity. The first deals with training effectiveness. It has been shown (Martin & Waag, 1980) that it is contrary to good training practice to make training an exact duplicate of certain real jobs. The training situation affords the opportunity for immediate feedback and enhanced stimulus cues which aid in training but which may not be available on actual equipment. When these features are incorporated in a simulator, the level of fidelity is lowered.

A second reason is the cost effectiveness of lower fidelity simulators. A simulator may be less costly than the actual equipment and if it can be designed with a lower level of fidelity and still provide adequate transfer of training, even more money can be saved.

The third reason for departure from perfect fidelity is the safety of the training. It may be too dangerous to train people on the actual equipment. Not only could individuals be injured but the actual equipment may be damaged if certain malfunctions are induced for the purposes of training.

The final reason given by Blaiwes et al. is the technological barriers to duplicating the operational environment. It may not always be possible to produce a training simulator that exhibits perfect fidelity. The level of fidelity necessary to produce trained personnel must be determined by accounting not only for the previous considerations but also for considerations inherent in the training context. Training context is defined as the way in which a training simulator is incorporated into a specific program of instruction. Although we may see fidelity as a central question in any attempt to design or evaluate a training simulator, it is not. The central question is not its fidelity but its training effectiveness. As we shall see, fidelity interacts with several parameters to determine training effectiveness.

FIDELITY AND TRAINING EFFECTIVENESS

The question of the necessary level of fidelity has been asked ever since simulators began to be used in training. Not much progress was made in determining fidelity requirements until it was realized that fidelity is not really the question at all. Bunker (1978) states that progress was made only when "instead of pondering how to achieve realism, we should ask how to achieve training" (p. 291).

The same point was made by Kinkade and Wheaton (1972) several years earlier. "The overall level of fidelity required in a training device is partially determined by the desired amount of transfer of training" (p. 679).

What these statements tell us is that fidelity is not a concept that may be discussed in isolation. The effect of fidelity on training effectiveness is not simple. It is modified by the total context in which the equipment is used.

Fidelity and the Training Context

Micheli (1972) makes the point that it may be more important how a device is used than how it is designed. Montemerlo (1977) states that the training effectiveness of a simulator is a function of the total training environment and not just the characteristics of a particular piece of equipment. Wheaton et al. (1976) concluded after an extensive review of fidelity literature that fidelity per se is not sufficient to predict device effectiveness and that the effect of fidelity varies as a function of the type of task to be trained. It becomes increasingly clear that we cannot productively deal with the concept of fidelity in isolation but rather as a function of total training context--which includes the training tasks, the stage of learning of the trainees, and the instructional system designed to train the tasks. Training effectiveness (i.e., the amount of transfer of training from the simulator to the actual equipment in a specific context) may be used to determine necessary simulator fidelity levels.

Fidelity and Type of Task

Several authors have made the point that we must define necessary fidelity levels in terms of the tasks which must be trained. Different tasks may require different levels of fidelity. Fink and Shriver (1978) distinguish between the necessary instruction for maintenance tasks versus that needed for operational tasks. Maintenance training should entail "instruction in decision processes to a greater degree than operations training. This instruction must include formulation of decision rules, identification of decision alternatives, and actual decision making" (p. 5). The fidelity level necessary for decision making may be very different than that necessary for operating the controls on a piece of equipment. The important point here is that we are attempting to train individuals to behave in certain ways and that the ultimate behaviors must guide our choice of fidelity levels. Miller (1980) states the point in this way:

> While physical identity of operational and training equipment does facilitate transfer, the controlling factor is not physical congruence but the (sometimes subtle) cues that guide the behavior involved in the performance of a task. Careful analysis and exploitation of these cue/behavior patterns is the basis of all synthetic or simulation-based approaches to training (p. 5).

Stated another way, "The important point is that the behavioral requirements dictate the physical characteristics rather than some perceived physical fidelity dictating behavior" (Matheny, 1978, p. 4).

What is necessary is for us to bridge the gap between the output behaviors which we desire and the input behaviors which the trainees arrive with.

Fidelity and Stage of Learning

An important consideration in determining the fidelity levels necessary to build this "behavioral bridge" is the stage of learning in which we find

the trainee. Fink and Shriver (1978) discuss four stages of learning of which each has different general training objectives and which lend themselves to the use of different types of training devices with different levels of fidelity. Table 3 shows these stages of learning and their relationship to training objectives and types of training devices. Fink and Shriver are of the opinion that "no one class of training aid or devices need carry the entire training load" (p. 22). They feel it is more cost effective to train the first stages of learning on low fidelity devices before switching to more expensive simulators required in later learning stages. Kinkade and Wheaton (1972) make the same point. They delineate five stages of training for which different training devices are appropriate. Table 4 shows the types of training devices associated with these five stages of training.

Fidelity and Task Analysis

We can see that fidelity levels cannot be determined outside of the training context. The determination of the necessary fidelity becomes a repetitive process with the analysis of tasks and behavior objectives as its guiding principles. "The major decisions in this process are selection of the subset of tasks that will actually be trained in the device and determination of the degree of fidelity necessary to train each of the tasks in the subset" (Eggemeir & Cream, 1978, p. 18). Task analysis therefore is the important first step in determining not only fidelity requirements but also whether a simulator is necessary at all.

Tasks have been analyzed in various ways. Smode (1971) analyzes tasks as training objectives: what is to be trained, under what conditions the training will occur, and the standard of performance desired at the end of training. For each objective, tasks are stated in terms of performance elements, how these will be measured and the conditions under which performance occurs. Smode provides a detailed strategy for developing these training objectives. Similar strategies are provided in the guidebooks which were discussed above (Interservice Procedures, 1975; Lenzychi & Finley, 1980; Training Device Requirements Guide, 1979).

Another approach to task analysis is to rank each task in terms of its criticality, frequency, and difficulty (CFD) (Slenker & Cream, 1977; Eggemeir & Cream, 1978; Freda, 1979). Tasks that are rated high on these dimensions would be included in the training device with the fidelity level determined by a repetitive process. Freda (1979) also uses the CFD approach to provide a framework for analyzing learning tasks in terms of the information processing demands on the individual in the operational setting. "These information processing demands can be viewed as a sequential flow of three information processing stages" (p. 6).

The first stage is sensory input and "refers to the degree of CFD involved in the apprehension of operational stimulus parameters for suprathreshold input processing" (p. 9). The second stage is central processing and "refers to the degree of CFD involved in using cognitive skills and strategies for selecting the appropriate psychomotor output based on the sensory input" (p. 9). The third stage is psychomotor output and "refers

Table 3

General Relationship Between Stages of Learning, Training Objectives, and Types of Training Devices (Fink & Shriver, 1978, p. 23)

Stages of learning	General training objectives	Types of training devices
1st stage	Acquire enabling skills and knowledges	Demonstrators--wall charts, films, TV, mock-ups, etc. Nomenclature & parts location Trainers
2nd stage	Acquire uncoordinated skills and unapplied knowledges	Part-task trainers Procedures trainers
3rd stage	Acquire coordinated skills and ability to apply knowledges	Troubleshooting logic trainers Job segment trainers Skills trainers
4th stage	Acquire job proficiency in job setting	Operational equipment Actual equipment trainers

Table 4

Types of Training Devices Associated with Stages of Learning (adapted from Kinkade & Wheaton, 1972, p. 673)

Stages of learning	Types of training devices
Indoctrination	Films, TV, mockup
Procedural training	Photographs, nonfunctional mockup, functional mockup
Familiarization training	Functional equipment Part-task trainer
Skill training	Functional with man-machine dynamics Represented Part-task trainer
Transition training	Part-task simulator

to the degree of CFD involved in the expression of the appropriate behavioral response" (p. 9).

Depending upon the stage of the information processing demands in which a given task is classified and depending upon its CFD rating, the fidelity requirements of a simulator to train that task may be determined (Freda, 1979; Lenzychi & Finley, 1980).

An alternative (or perhaps complementary) approach to task analysis is to analyze the behavioral cues which stimulate the required performance (Pearson & Moore, 1978; Grumman, 1980). In this approach, the degree of fidelity necessary in the simulator is determined on the basis of the amount of information the students must derive from the cue to make the cue worthwhile. "The desired fidelity of a given cue is that level which will enable a trainee discrimination equivalent to that which he could obtain from that cue and similar cues provided by the operational equipment" (Grumman, 1980, p. 128). This approach would make a useful addition to the approach discussed above where tasks are analyzed in terms of CFD. Once it is determined that a given task is above the criterion level on CFD, it may then be analyzed in terms of its behavioral cues to determine the necessary level of fidelity to train the task.

Fidelity and the Trainee's Abilities

An important area of research which relates to task analysis is the determination of how the skills which are necessary for a given task relate to general abilities. This relationship has been utilized in rating tasks on CFD (Freda, 1979). Tasks have been organized into 11 general categories which are very close to general abilities (Aagard & Braby, 1976). Not only can these general learning categories be used to evaluate tasks in determining necessary fidelity levels, but it is also possible to use the output from such evaluations to determine which individuals should be selected for training in the first place. By testing individuals on basic abilities prior to their inclusion in training programs, it should be possible to screen out those trainees who do not possess the required abilities to benefit from a given training program. Again, we must keep in mind that the issue of fidelity should be secondary to the real issue, which is the production of well trained personnel. The "best" training course with perfect fidelity levels will not be productive if the trainees selected for the course do not have the requisite abilities to master the tasks trained in the course.

Fidelity and Psychological Principles

The determination of the necessary fidelity level for a training simulator may be facilitated if we are guided by established psychological principles in the design of the simulator. Adams (1979) discusses five psychological principles which should underlie the design and use of any simulator. These principles are (1) human learning is dependent on knowledge of results (KOR) so any simulator should incorporate KOR, (2) perceptual learning or the ability to extract information from stimulus patterns increases as a result of experience which may be provided on a simulator,

(3) if a response is to be made to a stimulus, then the stimulus and the control for response to it must be in the simulator, (4) transfer is highest when the similarity between the simulator and the actual equipment is high although transfer is possible with low similarity, and (5) the trainee must be motivated if learning is to occur. One additional principle (Grumman, 1980) is relevant. It is the phenomenon of perceptual constancy. This phenomenon occurs when familiar objects are perceived as maintaining their perceived characteristics almost independent of changes in stimulus conditions. This principle allows reduced fidelity in simulators to a certain point. Each of these principles should be taken into account when the fidelity levels of a simulator are determined.

Training Effectiveness as Determinant of Fidelity Requirements

As was stated previously, training, rather than fidelity, is the real issue. We are in the business of training individuals in specific tasks and all the hardware and software are simply aids in this training process. The necessary fidelity level becomes easier to determine by using training effectiveness as our criterion. The necessary fidelity level for a given simulator may be empirically determined by the training effectiveness of the simulator. As stated previously, training effectiveness may be operationalized as the amount of transfer of training from the simulator to the actual equipment. However, this method has problems as pointed out by Adams (1979). The most critical problem is the cost of transfer of training experiments. It would be very costly to design several simulators with different levels of fidelity, train individuals on them, and then evaluate the trainee's performance on actual equipment. However, this is the only method that will provide us with the empirical data necessary to determine fidelity requirements. It may be possible to make this method more cost effective by limiting the number of fidelity levels evaluated and by beginning our investigations with lower levels of fidelity. As Fink and Shriver (1978) wrote: "The answer to maintenance training lies not in how much but how little simulation to use. This is not to say that fewer simulators should be used, merely that low-cost, low-fidelity simulators should be employed where they can be made effective" (p. 26). Eddowes (1978) also said: "As soon as the capabilities of a simulator support practice of a set of training tasks, stop adding to it. Everything else the simulator does will cost more, and while it may not detract from training effectiveness, it probably won't add to it" (p. 53). Once we have determined that a lower fidelity level is adequate for a given simulator, it will not be necessary to evaluate simulators which incorporate higher fidelity levels. Let us now discuss some of the methodological issues involved in empirically determining necessary levels of simulator fidelity.

METHODOLOGICAL ISSUES

Several methodological issues arise when we attempt to empirically determine the necessary fidelity level for a simulator to train a given task. As was discussed earlier, various tasks will require different levels of fidelity as will different stages of the learning process. It is important that general guidelines be established for required fidelity levels and the only way to establish these guidelines is through empirical investigations

of the relationship between level of fidelity and training effectiveness. These empirical investigations should begin at a general level and proceed to a more specific level. The studies at the general level may be considered pilot studies which will direct later investigations focusing on specific tasks and specific configurations of training simulators.

The first step in the empirical investigation of the relationship between level of fidelity and training effectiveness is to develop a scale to measure level of fidelity. If we follow the definition of fidelity that was developed previously, we will have two factors to measure: the physical characteristics of the simulator (physical fidelity) and the informational or stimulus and response options of the equipment (functional fidelity).

We therefore need to measure the physical and functional aspects of fidelity before we can attempt to empirically determine how these factors relate to the training effectiveness of the simulator. An example of this two-factor approach to the measurement of fidelity is the work of Wheaton, Mirabella, and Farina (1971), Wheaton and Mirabella (1972), and Mirabella and Wheaton (1974). In these three investigations, two scales were used to measure the characteristics of training simulators. Panel lay-out indexes developed by Fowler, Williams, Fowler, and Young (1968) were used to measure the physical fidelity of the simulators. Another scale which was assumed to vary independently with the above scale was used to measure the functional fidelity of the simulators. This scale, called the Display Evaluative Index (DEI) was developed by Siegel, Miehle, and Federman (1962) and is a measure of the effectiveness with which information flows from displays to corresponding controls via the operator. This approach yields two fidelity measures which define the two aspects of fidelity. Depending on other parameters such as task type and level of training, these aspects would interact and lead to a given level of training effectiveness.

An example of the design for one of these pilot studies is shown in Figure 1. Here we see the two aspects of fidelity (physical and functional) being treated as factors in a 3 x 3 factoral design. Depending on how a fidelity factor fell on the measurement scale chosen for the experiment, each factor would be represented as low, medium, or high. Values in the cells of the design would be derived from measures of proficiency on the actual equipment.

The measurement of training effectiveness is another problem which must be solved if our empirical investigations are to be meaningful. While there are a variety of methodologies and measures that have been used to measure the training effectiveness of simulators, the transfer of training experiment is the most useful for experimental purposes (Adams, 1979). Of the various measures of training effectiveness that may be derived from a transfer of training experiment, the transfer effectiveness ratio (Provenmire & Roscoe, 1971) may be best adapted for this research. It has been used successfully in Army simulator effectiveness research (Holman, 1979). The transfer of a training type of study would have to be applied to each training task to determine the "best" combination of physical and functional fidelity for that task. A review of theories and models of transfer of training is provided by Wheaton et al. (1976).

		Physical fidelity		
		Low (control absent)	Medium (drawing)	High (3-D)
Functional fidelity	Low (doesn't work mechanically)			
	Medium (works with no effect)			
	High (works with effect)			

Figure 1. Sample design for a pilot study to determine the "best" combination of fidelity levels for a given task.

Once such pilot studies have narrowed our focus down to a few testable concepts, we may develop training programs which actually use simulators to train individuals. Then we can measure the level of training effectiveness on a given task. Our research efforts should determine the training effectiveness of every type of fidelity configuration. Data from these efforts may then be used to determine which configuration is most cost effective to produce the highest level of training effectiveness on a given task. If lower levels of fidelity produce adequate training effectiveness, then there is no necessity to produce simulators with higher fidelity. As was stated previously, more fidelity than is necessary may not reduce the efficiency of a simulator but it will probably not improve it either. Just enough fidelity to motivate the trainee while providing him or her with the necessary skills on the actual equipment is the goal to which we should strive. In this way we still provide the most cost effective training for the Army's personnel.

CONCLUSIONS AND RECOMMENDATIONS

Confusion surrounding the use of the term "fidelity" may be substantially reduced if we limit the use of the term and let fidelity refer only to the degree of similarity, both physical and functional, between a training device and the actual equipment for which the training was undertaken. By dealing with the configuration of the equipment itself, we have something concrete which we can manipulate to change the trainee's behaviors. Other concepts which have been discussed under the label "fidelity" are still useful but should be separated from the concept of fidelity by the use of other labels. We may then ask how fidelity interacts with these concepts. Many researchers have concluded that fidelity, as defined in this paper, interacts with at least four factors: the stage of learning of the trainee, the type of task to be trained and the way the simulator is used and accepted by students and instructors, and the individual sensory and perceptual differences among subpopulations of trainees. Further research needs to be conducted to at least generally determine how the above factors actually interact with the physical and functional configuration of training simulators in producing given amounts of transfer of training. Knowledge about the interaction of these factors with physical and functional fidelity will allow us to determine the principles of simulator training which produce the most effective training program for any given task. Once these principles are quantified we will then be able to determine not only the most effective simulator configuration but also the training context in which the simulator may be used most effectively.

The proposed definition of fidelity and the research strategy which uses this definition should enable us to quantify the concept of simulator fidelity for any given task. We may then use this data as one source of input to our efforts to prescribe simulator device characteristics for devices not yet produced and also to predict the training effectiveness of devices that already exist. Our efforts will pay off in more cost effective programs of instruction which better train individuals for the needs of the Army.

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